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THE COMPOSITION, STRUCTURE, AND HARD-
NESS OF SOME PERUVIAN BRONZE AXES.

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(Contributions from the Yale Peruvian Expedition,

ART. XII.—*The Composition, Structure, and Hardness of Some Peruvian Bronze Axes*; by H. W. FOOTE and W. H. BUELL.

DURING the summer of 1911, Prof. Hiram Bingham, while with the Yale Peruvian expedition in eastern Peru, obtained three bronze axes which appear to belong to the Inca period. These axes were turned over to the authors and form the basis of the present investigation.

In the photograph of the axes, fig. 1, we have numbered the specimens and given the dimensions. Nos. 1 and 3 were

FIG. 1.

found on the site of an old Inca settlement near the Pampaconas River in latitude $12^{\circ} 30' S.$ and longitude 73° . This river has not yet been mapped. It is a western branch of the Urubamba River, flowing nearly parallel and emptying into it at some point below Icharate. The settlement where these axes were found had been entirely deserted and all the original clearings were covered with forest. A few years ago, a small tract was cleared and it was in this new clearing that the axes were found. Axe No. 2 was found in the valley of the Urubamba River near Rosalina.

In our investigation, we have determined, first, the chemical composition of the axes; second, their micrographic structure, and third, their hardness. By comparing the structure of one of the axes with that of a new alloy of the same composition, we have been able to draw conclusions as to the methods used originally in making the axes.

The following results were obtained on analysis:

	No. 1	No. 2	No. 3
Tin	12.03	5.58	3.36
Copper	88.06	93.94	96.44
Iron	0.08	none	trace
Silver	none	0.65	none
Sulphur	0.35	0.08	0.23
Lead	none	trace	none
	<hr/> 100.52	<hr/> 100.25	<hr/> 100.03

The results show that the alloys are all bronzes which vary considerably in their percentage of tin and contain a small amount of sulphur. No. 2 also contains silver in small amount.

The alloys of copper and tin have been most thoroughly investigated by Heycock and Neville* and by Shepherd and Brough.† Their results show that alloys containing not more than approximately 10 per cent of tin consist entirely of a solid solution of tin in copper, stable at all temperatures below the melting point, and made up of so-called α -crystals. Alloys containing between 10 and 22 per cent of tin deposit on solidifying a mixture of α - and β -crystals. The β -crystals consist also of a solid solution of the two metals but contain more tin than the α modification. They are stable only above 480° C. and if cooled slowly below this transition temperature, δ -crystals are formed. These are extremely brittle and an alloy containing them cannot be successfully worked either hot or cold. If, however, the alloy is quenched rapidly from a temperature above 480° C., a mixture of α - and β -crystals results which is characterized by great strength and tenacity. This alloy can be forged. It is evident, therefore, that the properties of an alloy whose composition is between the limits mentioned above, depend very largely on its previous heat treatment, since the properties of β - and δ -crystals are different.

Referring to the analyses of the bronzes, No. 1 appeared to be the most interesting from a metallurgical standpoint, containing, as it does, 12 per cent of tin, or enough to yield either β - or δ -crystals. For comparison, a bar of metal was cast of nearly the same composition as this axe. It contained:

Tin	12 per cent
Copper	88 “

From this bar an axe was forged which we shall call the “new axe.” In forging the new axe, we endeavored first to work it hot without paying much attention to the temperature, but found this could only be done above 500° C. After heating followed by slow cooling, the alloy was still extremely brittle.

* Phil. Trans., ccc A, 1, 1903.

† Jour. Phys. Chem., x, 630, 1906.

Under a hammer, it broke in pieces. By heating above 500°C . and quenching, however, to retain the β -crystals, we were able to forge the axe cold without any material difficulty, but it was found necessary to anneal at intervals during the forging, heating each time above 500°C . and quenching.

Photographs were made showing the microstructure of the original casting from which the new axe was made, before the alloy had been worked or annealed. Fig. 2 shows this structure, which is characteristic of alloys of this type, made up of fern-like or kidney-shaped 'casting crystals.' Figs. 3 and 4 show the structure of the new axe in its finished condition after annealing and forging as described above. Fig. 3 was taken near the center of the axe and shows the crystals with no distortion. Fig. 4 was taken near the edge and shows slight distortion of the crystals due to forging. From a comparison of figs. 2, 3, and 4, it is evident that the structure has been entirely changed by annealing and forging.

The original axe, No. 1, shows from its shape, and from the

FIG. 2.

FIG. 3.

FIG. 2 Showing casting structure of new axe.

FIG. 3. Showing structure on center of finished axe. Made from metal shown in fig. 2.

marks on it, that it has been forged. The original shape of the casting cannot be told, but there can be no doubt that the shape has been materially changed by the forging. Figs. 5 and 6 show the micro-structure of this axe. It is similar in type to that shown in figs. 3 and 4 and entirely different from that in fig. 2. The size of the crystals is different. That, however, is controlled by the temperature before quenching. The size of crystals produced by annealing is usually a

FIG. 4.

FIG. 5.

FIG. 4. Showing structure on edge of new axe. Made from metal shown in fig. 2. Crystals somewhat distorted due to hammering.

FIG. 5. Showing crystals near edge on axe No. 1. The structure of the metal was poor and it was impossible to get a very good etching.

function of the temperature and the size can be increased by raising the temperature. The time of heating is not important except at low temperatures or when the heating has been continued for a long time, for example, for several days.

FIG. 6.

FIG. 7.

FIG. 6. Showing crystals in center of axe No. 1. The structure of the metal was poor and it was impossible to get a very good etching.

FIG. 7. Showing fine crystals, which occur only at one point of edge on axe No. 3.

Taking into account the facts of micro-structure and that the axe has been forged, it is fair to infer that after casting the original alloy, it was heated to a temperature considerably above 500° and either forged hot or quenched suddenly and forged cold. This required a very considerable degree of skill on the part of the original makers.

FIG. 8.

FIG. 8. Showing crystals on axe No. 3, a short distance from edge on cross section.

We were unable to obtain an etching of axe No. 2. Apparently the silver in it gave trouble by dissolving in all the etching solutions which we tried and reprecipitating on the surface, leaving a dark deposit which prevented the microstructure from being observed. Figs. 7 and 8 show the microstructure of the fragment of axe No. 3. Both views were taken on the broken section. The fine crystals occurred close to the edge at the extreme left as shown in fig. 1 and the coarse crystals occurred nearer the center. The axe was therefore very unevenly heated, either in the original annealing or at some time afterward.

None of the old axes are very hard. The following table gives the results of the scleroscope tests:

	New axe	No. 1	No. 2	No. 3
Edge.....	36	26	18	18
Center.....	34	24	20	..

The hardness was taken with the Shore scleroscope and it varies somewhat with the percentage of tin as would be expected, but shows nothing at all unusual. In fact, the hardness of the old axes is considerably less than that of the new axe, which is probably due to coarser structure as well as to composition. The values given in the table are expressed in empirical units and merely give comparative values among themselves. For the sake of comparing the hardness of the axes with that of another metal, it may be well to add that a piece of cast brass has a hardness on the same scale of 11 or 12 units.

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